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INT CL^6 **H01L**
ON LINE,W.P.I.

(54) Abstract Title

Lenses for semiconductor light emitting devices

(57) A semiconductor lens 20 is integrally formed with a laser or light-emitting diode by growing alternating layers 21 of a graded aluminium-containing semiconductor material, such as AlGaAs, and layers 22 of a non-aluminium-containing semiconductor material, such as GaAs, which serve to increase the structural strength. The layers 21 are graded so that the bottom layer 21 has the lowest aluminium grading and the top layer 21 has the highest aluminium grading. A GaAs cap layer 23 is provided to prevent oxidation through the upper surface of the top layer 21. Selective oxidation is then effected from the side so as to produce a shaped region 25 of unoxidised semiconductor material of refractive index N_1 and a region 26 of oxidised semiconductor material of refractive index N_2. Optionally the layer 21 is then selectively etched so as to remove the oxidised semiconductor material. Whether or not such material is removed, a high refractive index lens is produced with a surrounding low refractive index region. This avoids the need to use an external optical arrangement to provide the required beam shape, and thus enables a more compact system to be produced.

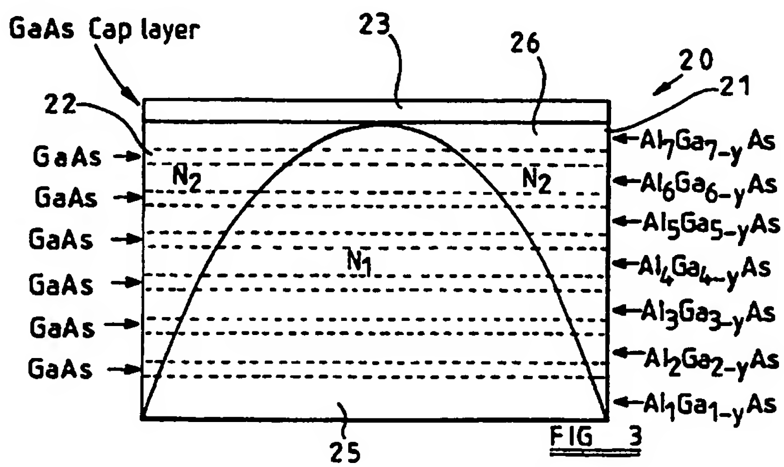


FIG 3

GB 2 327 533 A

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

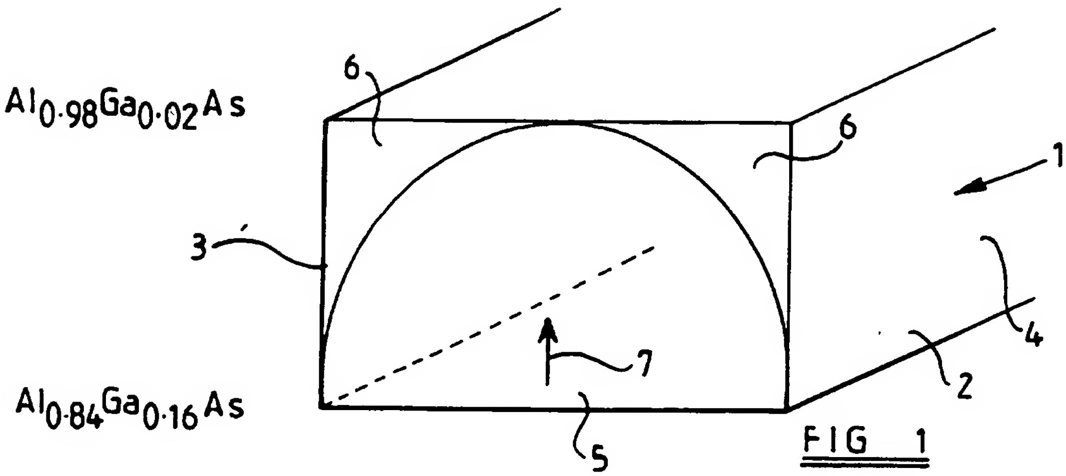


FIG 1

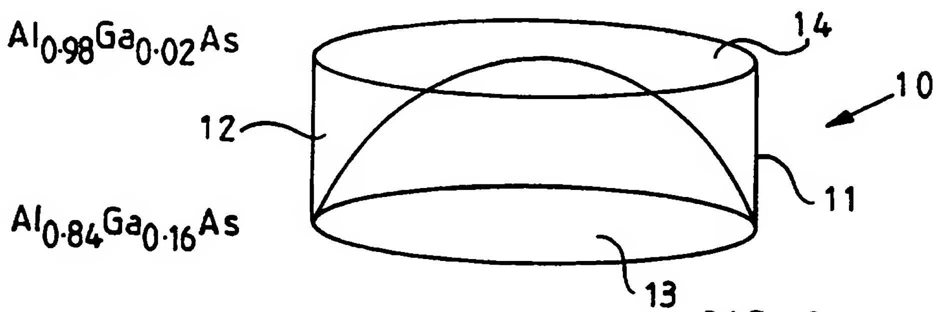


FIG 2

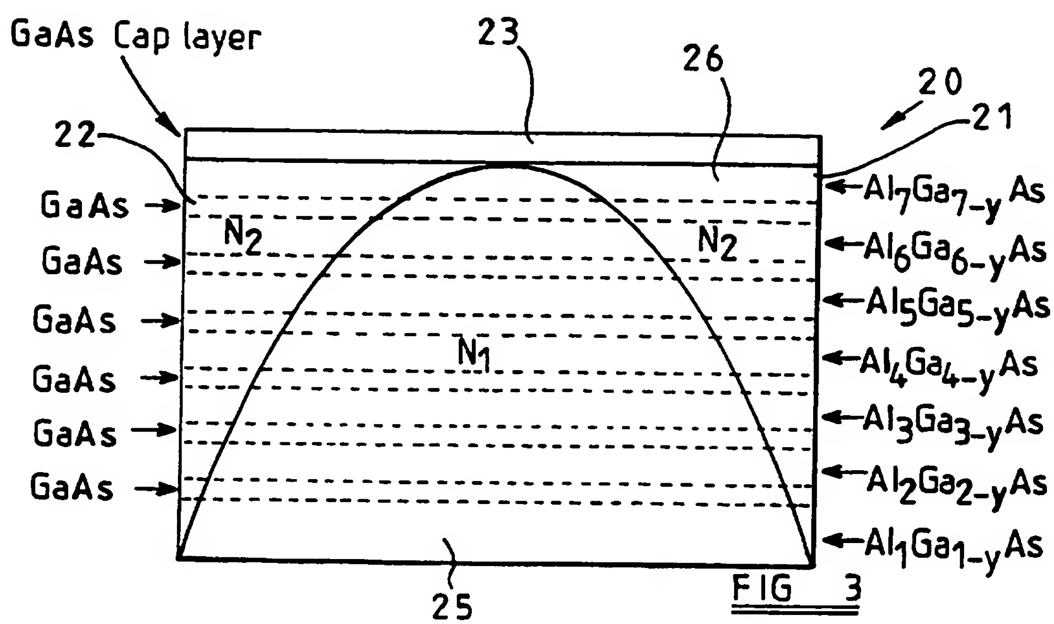


FIG 3

FIG 4

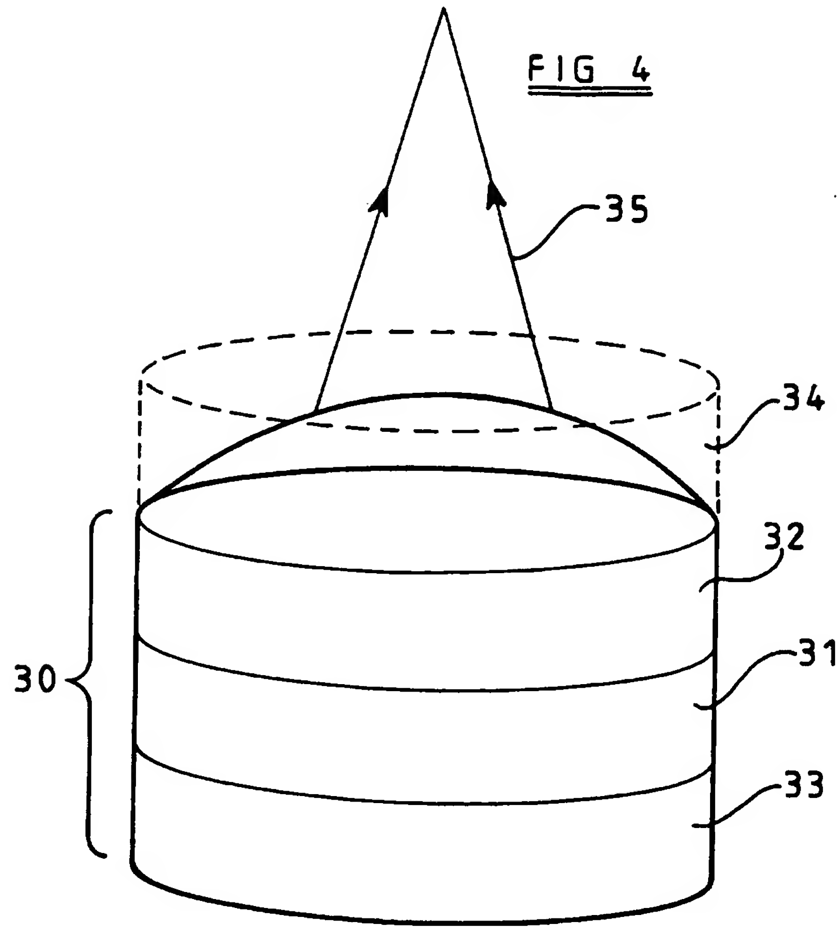


FIG 5

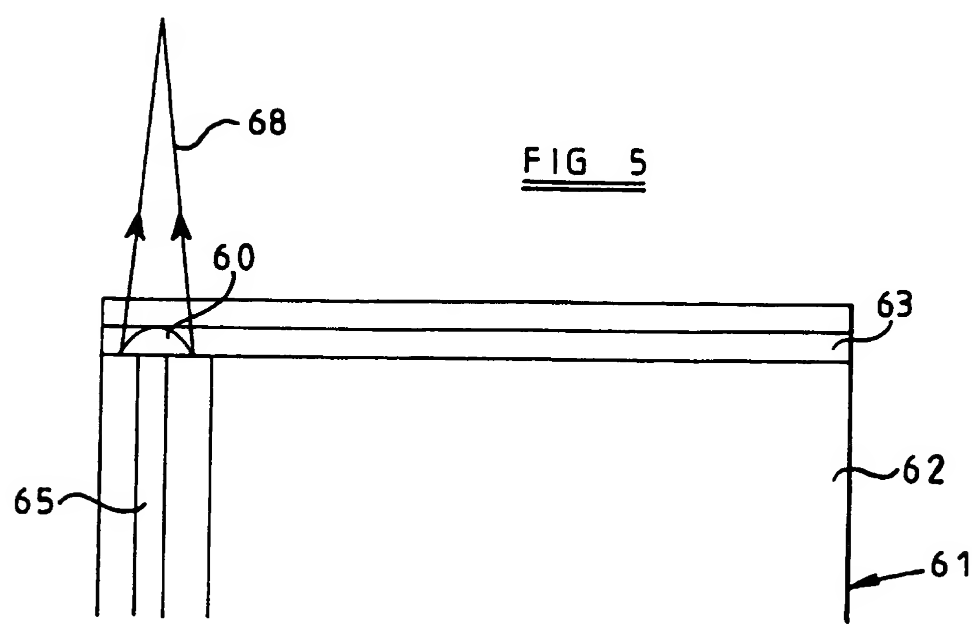


FIG 6

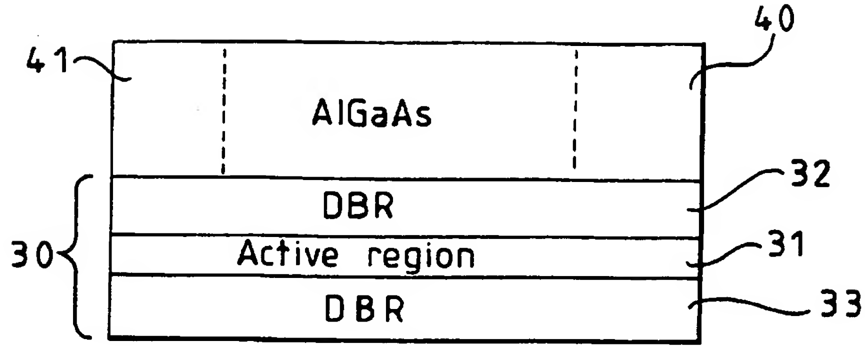


FIG 7

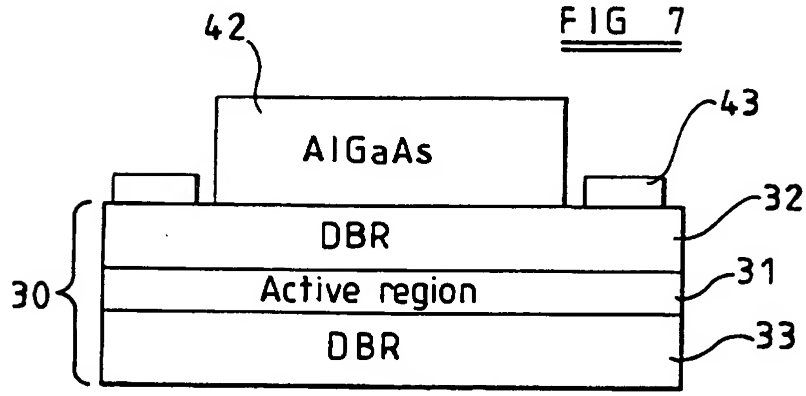
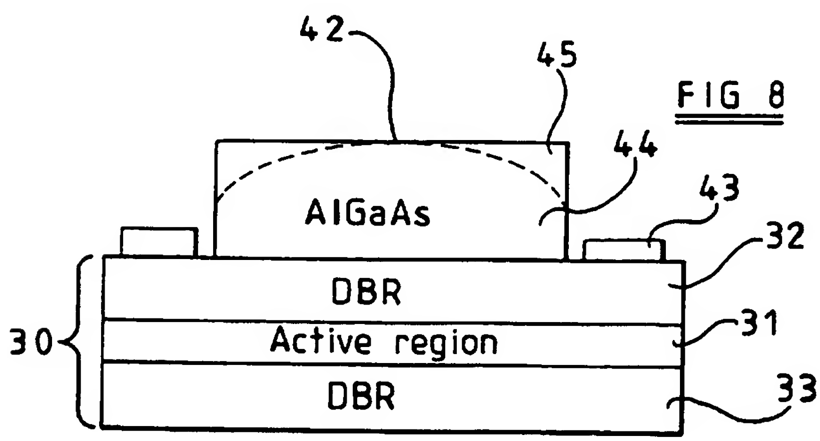


FIG 8



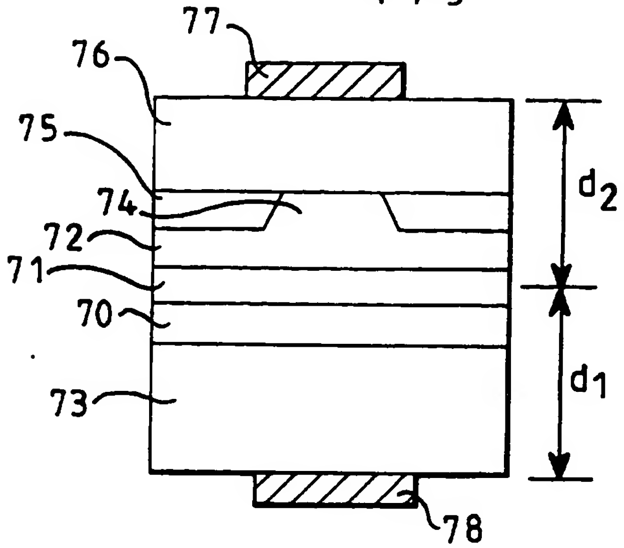


FIG 9

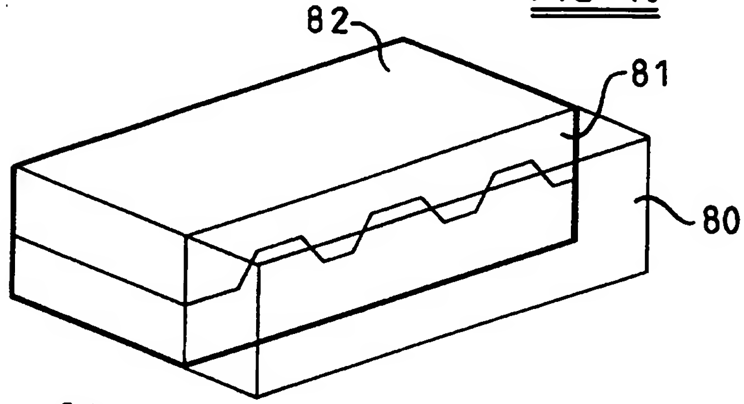


FIG 10

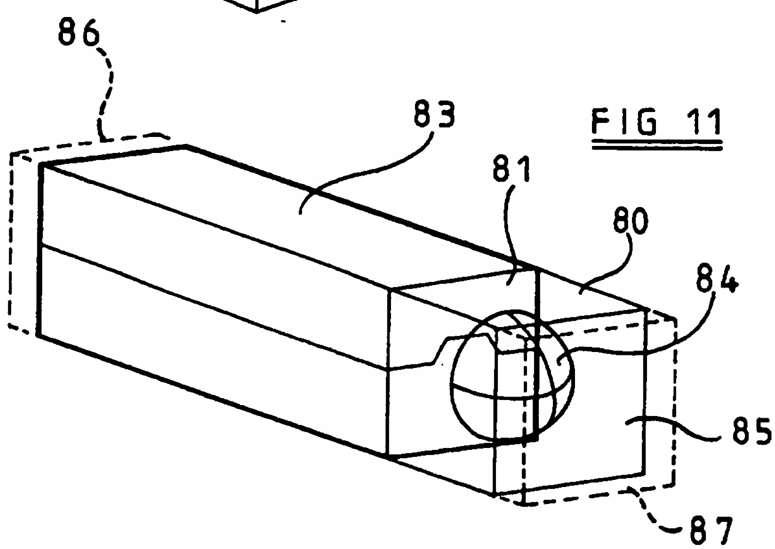
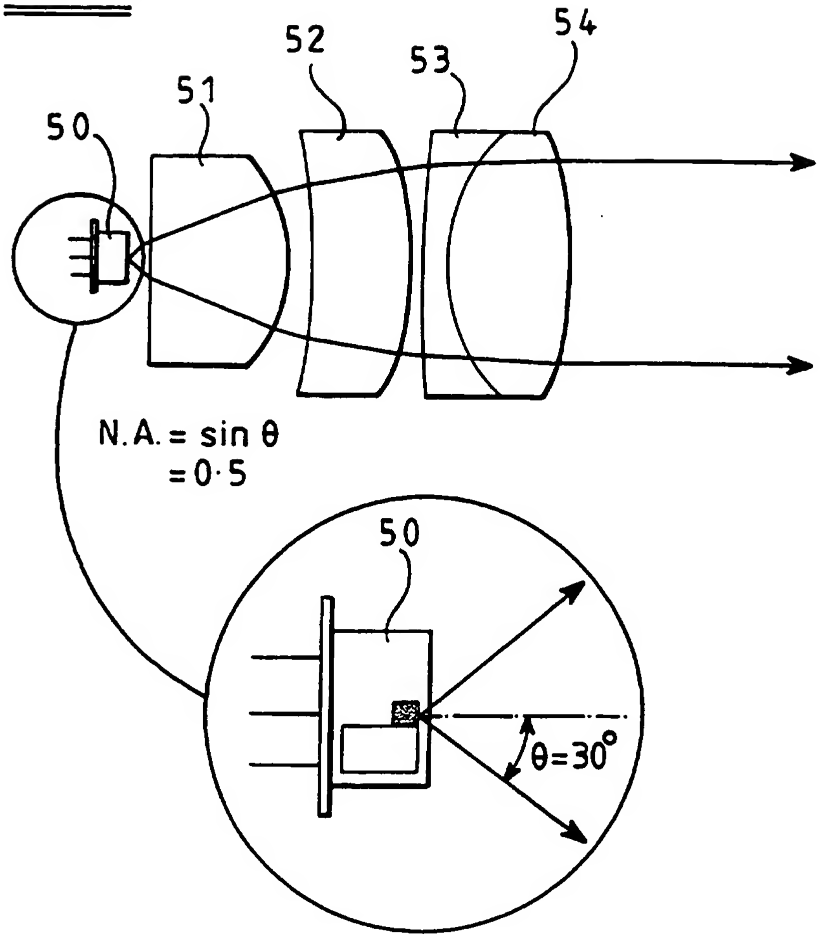


FIG 11

FIG 12



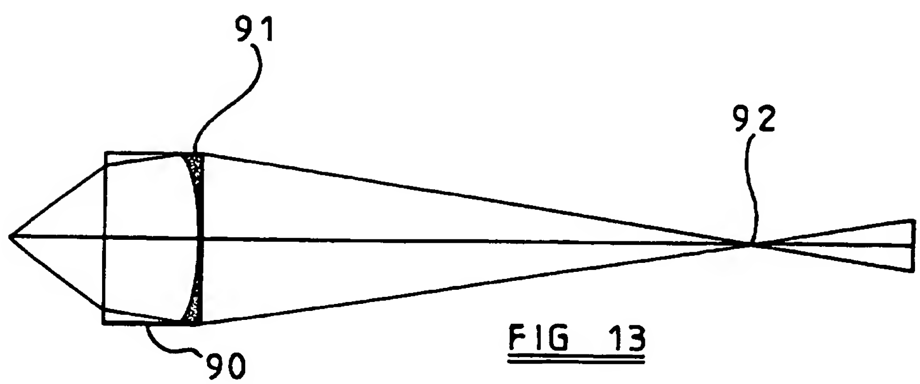


FIG 13

"Lenses"

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This invention relates to lenses and is concerned more particularly, but not exclusively, with semiconductor optoelectronic devices, such as lasers and light-emitting diodes, incorporating such lenses.

A semiconductor laser system typically comprises a semiconductor laser device, such as a planar edge emitting laser or vertical cavity surface emitting laser (VCSEL), and an external optical arrangement incorporating at least one lens, typically made of glass, for forming a collimated or focussed beam from the radiation emitted by the laser. The need to provide such an external optical arrangement not only increases the cost of fabrication of the laser system but also renders the laser system more bulky than would be the case if such an external optical arrangement were not provided.

O. Blum et al, Electronic Letters 31, 1, p. 44 (1995) proposes a VCSEL provided with an integrated refractive polyimide microlens which serves to reduce beam divergence of the laser radiation to 1 to 2°. Such a polyimide microlens relies on refraction of the radiation at the interface of the polyimide material and the surrounding air, and thus the degree of collimation provided by such a lens is limited by the fact that there is a relatively small refractive index difference between the polyimide lens (with a refractive index of about 1.5) and air (with a refractive index of about 1.0). Thus such a polyimide microlens would require an increase in its radius of curvature to provide

improved collimation, and this would be difficult to achieve with the proposed method of fabricating such a lens.

It is an object of the invention to provide an improved lens which may be integrated with a semiconductor optoelectronic device, and a method of fabricating such a lens.

According to a first aspect of the present invention there is provided a lens comprising a region of semiconductor material shaped by selective oxidation of a layer of semiconductive material so as to leave said region of semiconductor material unoxidised and adapted to focus a beam of radiation.

Such a lens may be produced from a graded aluminium semiconductor alloy which is selectively oxidized to form a high refractive index lens with a surrounding low refractive index oxide region. The lens shape for a particular application can be produced by grading the aluminium composition in such a manner as to produce the required lens curvature by selective oxidation of the semiconductor alloy depending on the aluminium content of the alloy. Such a lens may be integrally formed with a semiconductor optoelectronic device, such as a planar edge emitting laser or a vertical cavity surface emitting laser (VCSEL) or a resonant cavity light emitting diode (RCLED), so as to form a collimated or focussed beam from the radiation emitted by the device. This avoids the need to provide an external optical arrangement

incorporating at least one glass lens to provide the required beam shape, and thus enables a more compact system to be produced.

The shaped region of unoxidised semiconductor material may define a refractive index interface with one or more adjacent regions of oxidised semiconductor material, or alternatively the shaped region of unoxidised semiconductor material may define a refractive index interface with air, as a result of removal of the oxidised semiconductor material.

Preferably the layer of semiconductive material has a composition which is graded across the layer such that the oxidation rate of the material varies across the layer, and most preferably the layer comprises a series of sublayers differing in the proportion of a common constituent of each sublayer such that the proportion varies monotonically across the layer from a minimum value to a maximum value. Optionally the sublayers of semiconductor material may be separated by intermediate layers of semiconductor material which do not contain said constituent.

According to a second aspect of the present invention there is provided a method of forming a lens comprising growing a layer of semiconductive material, and selectively oxidising the semiconductor material of the layer so as to form a region of unoxidised semiconductor material which is shaped to focus a beam of radiation.

The invention further provides an optical system comprising a surface emitting optoelectronic device, and a lens according to the first aspect which is integrally formed with said surface emitting optoelectronic device.

The invention also provides an optical system comprising an edge emitting optoelectronic device, and a lens according to the first aspect which is integrally formed with said edge emitting optoelectronic device.

Furthermore the invention provides a method of forming an optical system comprising the steps of forming a surface emitting optoelectronic device, and forming a lens by the method of the second aspect, wherein the layer of semiconductor material is grown on a surface of said surface emitting optoelectronic device so that the lens is integrally formed with said surface emitting optoelectronic device.

The invention also provides a method of forming an optical system comprising the steps of forming an edge emitting optoelectronic device, and forming a lens by the method of the second aspect, wherein the layer of semiconductor material is grown on an edge facet of said edge emitting optoelectronic device so that the lens is integrally formed with said edge emitting optoelectronic device.

In order that the invention may be more fully understood, reference will now be

made, by way of example, to the accompanying drawings, in which:

Figures 1 and 2 are schematic diagrams of two different semiconductor oxide lenses in accordance with the invention;

Figure 3 is a schematic diagram illustrating a multilayered semiconductor oxide lens in accordance with the invention;

Figure 4 is a schematic diagram of a VCSEL or RCLED structure provided with an integrated semiconductor oxide lens in accordance with the invention;

Figure 5 is a schematic diagram of a planar edge emitting laser provided with an integrated semiconductor oxide lens in accordance with the invention;

Figures 6, 7 and 8 are diagrams illustrating successive fabrication steps of a semiconductor oxide lens in accordance with the invention;

Figures 9, 10 and 11 are diagrams illustrating successive fabrication steps of a further semiconductor oxide lens in accordance with the invention;

Figure 12 is a schematic diagram of a laser diode having four collimating lenses which may be in the form of semiconductor oxide lenses in accordance with the invention; and

Figure 13 is a lens trace diagram of a semiconductor oxide lens in accordance with the invention.

The semiconductor oxide lenses in accordance with the invention which will now be described are fabricated from graded aluminium semiconductor alloy which is selectively oxidized to form a high refractive index shaped region with a surrounding low

refractive index oxide region. Selective oxidation of semiconductor materials containing aluminium has previously been proposed in the fabrication of lasers and light emitting diodes. For example, F.A. Kish et al, Appl. Phys. Lett. 59, 1755 (1991), and S.A. Maranowski et al, Appl. Phys. Lett. 63, 1660 (1993) have proposed index-guided in-plane lasers incorporating a quantum well heterostructure in which optical and current paths are defined by alternating stripes of semiconductor material of high refractive index and oxide of low refractive index. Furthermore D.L. Huffaker et al, Appl. Phys. Lett. 66, 3096 (1995) proposes a resonant cavity light-emitting diode (RCLED) incorporating a Bragg reflector formed by selective oxidation of semiconductor material containing aluminium. Also D.L. Huffaker et al, Appl. Phys. Lett. 65, 97 (1994), K.D. Choquette et al, Electron. Lett. 30, 2043 (1994), Y. Hayashi et al, Electron. Lett. 31, 560 (1995), and G.M. Yang et al, Electron. Lett. 31, 886 (1995) disclose vertical cavity surface emitting lasers (VCSEL) in which current apertures are defined by selective oxidation of semiconductor material containing aluminium. Such a selective oxidation process is described for aluminium semiconductor compound material of the form $Al_xGa_{1-x}As$ in J.M. Dallesasse et al, Appl. Phys. Lett. 57, 2844 (1990), A.R. Sugg et al, Appl. Phys. Lett. 62, 1259 (1993), A.R. Sugg et al, Appl. Phys. Lett. 74, 797 (1993), K.D. Choquette et al, Electron. Lett. 30, 2043 (1994), US Patents Nos. 5373522 and 5262360, and International Patent Publications Nos. WO 93/20581 and WO 95/28003. Furthermore such a selective oxidation process for an aluminium semiconductor compound material of the form $(Al_xGa_{1-x})InP$ has been disclosed in F.A. Kish et al, Appl. Phys. Lett. 59 (3), 354 (1991). Such oxidation transforms selected parts of the material

into aluminium oxide which is insulating and has a refractive index of about 1.5, which is much lower than the refractive index of about 3.5 of a typical semiconductor material. Furthermore the lateral oxidation rate varies over two orders of magnitude for $Al_xGa_{1-x}As$ alloy compositions ranging from $1.0 \le x \le 0.84$ which enables a high degree of selectivity in the oxidation of a suitably graded aluminium semiconductor alloy. However none of these prior references teaches the fabrication of a semiconductor lens by selective oxidation.

The manner in which a semiconductor oxide lens in accordance with the invention may be produced from the material AlGaAs will now be described with reference to the drawings. Although none of the prior publications referred to above discloses such a semiconductor oxide lens or a method of fabricating such a lens, it should be understood that a number of the fabrication techniques referred to in those publications may be used in the production of such a lens, and accordingly the techniques discussed in those publications are imported herein by reference. Furthermore it should be understood that a similar method may be used to produce a semiconductor oxide lens from a wide range of further materials, such as AlInP, AlGaP, AlAsSb and AlGaN for example, and the references to AlGaAs below are to be taken merely as illustrative and not as limiting the scope of the invention. As is well understood, the material for the lens is chosen in dependence on the required emission wavelength of the device, in order to avoid light absorption by the lens.

Figure 1 diagrammatically shows a plano-cylindrical lens 1 in accordance with the invention which has been fabricated by growing a graded layer 2 of $Al_xGa_{1-x}As$ of substantially constant thickness on a suitable semiconductor substrate (not shown), where $0.98 \leq x \leq 0.84$ from top to bottom of the layer. In fabrication of such a lens 1 a cap layer of semiconductor material, such as GaAs, was deposited on the layer 2, and areas of the cap layer were then selectively etched away so that the part of the cap layer remaining was located over the region of the layer 2 where the lens 1 was to be formed, using a conventional technique. In this technique a film of photoresist was first applied to the layer, the film was selectively exposed and selected areas of the film were removed chemically prior to the required areas of the cap layer being etched using the photoresist film as a mask. The layer 2 was then subjected to an oxidising atmosphere at elevated temperature so as to cause oxidation of those areas not masked by the cap layer.

As will be described in more detail below, the oxidation of the layer 2 may be effected from two opposite sides 3 and 4 of the layer, the degree to which oxidation occurs from each side being controlled by the grading of the aluminium composition of the layer 2 from the bottom to the top so that the layer 2 has a relatively low aluminium grading, such as $Al_{0.84}Ga_{0.6}As$, at the bottom, and a relatively high aluminium grading, such as $Al_{0.98}Ga_{0.02}As$, at the top. The oxidation times and temperatures appropriate to such a process would be understood by a person skilled in the art from the disclosure of J.H. Kim et al, "Lateral Wet Oxidation of $Al_xGa_{1-x}As$-GaAs depending on its structures",

Appl. Phys. Lett. 69, 3357 (1996). The selective oxidation rate is up to two orders of magnitude faster for the high aluminium composition ($x = 0.98$) as compared with the low aluminium composition ($x = 0.84$). Thus, with suitable choice of grading, the required plano-cylindrical shaped region 5 of unoxidized semiconductor material may be produced bounded on two opposite sides by regions 6 of oxidized semiconductor material. As a result of the large difference between the refractive index of the semiconductor material ($n \sim 3.5$) and the refractive index of the oxidized semiconductor material ($n \sim 1.5$), light emitted in the direction 7 in Figure 1 will be focussed by the lens 1. This is shown more particularly in the trace diagram of Figure 13 in which the unoxidized semiconductor material of refractive index $n = 3.5$ is denoted by 90, the oxidized semiconductor material of refractive index $n = 1.5$ is denoted by 91 and the focus is at 92.

Figure 2 diagrammatically shows a plano-convex lens 10 in accordance with the invention. The lens 10 can be fabricated in a similar manner to the lens 1 of Figure 1 except that, in this case, the oxidation takes place from around the whole peripheral surface 11 with the result that the graded $Al_xGa_{1-x}As$ layer 12 is oxidized from the periphery with the upper part of the layer 12 being oxidized at a faster rate than the lower part of the layer 12 as before, so that the required plano-convex shaped region 13 of unoxidized semiconductor material is produced surrounded by the region 14 of oxidized semiconductor material. As in the previous example oxidation does not occur at the bottom and top surfaces of the semiconductor layer 12 due to the fact that the

layer 12 is grown on a suitable substrate and a cap layer is provided on top of the layer 12. Other lens shapes may be fabricated in a similar manner.

Figure 3 diagrammatically shows the form of a multilayered semiconductor oxide lens 20 in accordance with the invention. In this case the lens 20 consists of alternating layers 21 of a graded aluminium-containing semiconductor material, such as AlGaAs for example, and layers 22 of a non-aluminium-containing semiconductor material, such as GaAs for example, which serve to increase the structural strength of the lens. The layers 21 are graded as shown so that the bottom layer 21 has the lowest aluminium grading $Al_1Ga_{1-y}As$ and the top layer 21 has the highest aluminium grading $Al_7Ga_{7-y}As$. A GaAs cap layer 23 is provided to prevent oxidation through the upper surface of the top layer 21. As in the previous examples described, selective oxidation is effected from the side so as to produce the shaped region 25 of unoxidized semiconductor material of refractive index N_1 and the region 26 of oxidized semiconductor material of refractive index N_2 to impart the necessary lens properties. The GaAs layers 22 provide additional directionality to the oxidation of the AlGaAs layers 21, thus preventing anisotropic oxidation of the layers 21.The provision of alternating layers of aluminium-containing semiconductor material and non-aluminium-containing semiconductor material can be expected to increase the structural strength of the lens, as compared with the previous examples in which only graded layers of aluminium-containing semiconductor material are provided, although the refractive index difference between the oxidized and unoxidized regions of the semiconductor material would be less, and the radius of

curvature of the lens would be stepped rather than continuous which may slightly affect the optical path of the lens.

In a modification of the above-described arrangements a further fabrication step may be incorporated in which, after selective oxidation of the layer of semiconductor material has been effected, the layer is selectively etched so as to remove the oxidized semiconductor material whilst leaving the unoxidized semiconductor material in place, so as to form a shaped lens having an air/semiconductor interface at which there is a large difference between the refractive index of the semiconductor lens ($n \sim 3.5$) and the refractive index of air ($n \sim 1.0$).

It will be appreciated that any of the semiconductor oxide lenses in accordance with the invention described above may be formed as a integral part of a semiconductor optoelectronic device, such as a VCSEL or RCLED. Figure 4 is a schematic diagram of a VCSEL or RCLED structure 30, comprising an active region 31 sandwiched between two distributed Bragg reflector (DBR) mirrors 32 and 33, grown by standard MOCVD or MBE growth techniques and formed with an integral plano-convex semiconductor oxide lens 34 so that light emitted by the active region 31 is focussed by the lens 34 as shown by the rays 35. VCSEL devices emit a low divergence (~ 5°) circular beam, and the light emitted by the VCSEL (or RCLED) can be focussed by the lens 34 into an optical fibre or optical interconnection device. Since the lens 34 is an integral part of the VCSEL or RCLED structure, it is relatively easy to fabricate the lens

by growing a suitable graded $Al_xGa_{1-x}As$ layer directly on top of the structure 30 followed by selective oxidation of the layer as described above. A particular advantage of the semiconductor oxide lens described comprising a region of semiconductor material of large refractive index surrounded by an oxidized region of low refractive index is that, since the top surface of the lens is flat, it is a straightforward matter to deposit further layers on top of the lens, such as $\lambda/4$ anti-reflection coatings, multilayer DBR mirrors and the like.

A method of fabricating such a semiconductor oxide lens on top of such a VCSEL or RCLED structure 30 will now be described with reference to Figures 6, 7 and 8. In a first step, as shown in Figure 6, a graded AlGaAs layer 40 having a grading as described in any of the preceding examples is grown on top of the structure 30, and the layer 40 is then selectively etched after use of a conventional photoresist technique as described above to define the regions 41 to be etched. After etching a circular island 42 of AlGaAs is left, and, in a subsequent step shown in Figure 7, a p-type ring contact 43 is applied to the structure so as to surround the AlGaAs island 42. The ring contact 43 serves to symmetrically inject carriers into the active region of the device, whilst permitting light to escape through the centre of the ring. The etching is stopped before the level of the mirror 32 is reached. The exposed edges of the graded AlGaAs island 42 are then subjected to selective oxidation as shown in Figure 8 so as to produce the shaped region 44 of high refractive index semiconductor material surrounded by the region 45 of low refractive index oxidized material constituting the lens. Alternatively

the selective oxidation step may be carried out prior to deposition of the ring contact 43.

It is also possible for a semiconductor oxide lens in accordance with the invention to the applied to a planar edge emitting laser which emits a high divergence beam of asymmetrical form. In this case the half-angle beam divergence in the direction perpendicular to the active layer can be as large as 30°. In certain applications of such a laser in which a collimated or focussed beam of light is required, such as in an optical disk player, the divergent beam has to be corrected by use of a system of collimated lenses, as shown in Figure 12 for example in which the beam emitted by a laser diode 50 is collimated by four lenses 51, 52, 53 and 54. Such collimating lenses are expensive and bulky.

Figure 5 shows a semiconductor oxide lens 60 which is fabricated on the end facet of a planar edge emitting laser 61 comprising a substrate 62, an oxide layer 63 and an active region 65, the lens 60 serving to collimate or focus the emitted laser light as shown by the rays 68 in Figure 5. The fabrication of such a lens 60 will now be described with reference to Figures 9, 10 and 11. Initially a buried ridge structure is fabricated by successively growing an n-doped layer 70, an active region 71 and a p-doped layer 72 on an n-doped GaAs substrate 73, and then using photolithography and etching techniques to produce a ridge 74, followed by re-growth of n-doped GaAs to form a current blocking layer 75 and regrowth of p-doped GaAs to form a p - GaAs layer 76, in accordance with the standard techniques for fabrication of edge emitting

lasers. Having produced such a buried ridge structure, a p-type metal contact 77, typically of AuNi, is deposited on the p-GaAs layer 76, and the substrate 73 is lapped so that the distance d_1 from the bottom of the substrate 73 to the centre of the active region 71 is substantially equal to the distance d_2 from the centre of the active region 71 to the top of the layer 76. An n-type contact 78, typically of AuGeNi, is then deposited on the bottom of the substrate 73.

Having completed these fabrication steps so as to produce a series of such ridge structures on a single slice, the slice is cleaved into strips and a graded AlGaAs layer 80 is grown on the edge facet 81 of each strip 82. The strip 82 is then cleaved to produce individual devices and the layer 80 on the facet 81 of each device 83 is selectively oxidized according to the techniques already discussed so as to produce the shaped region 84 of high refractive index semiconductor material surrounded by the region 85 of low refractive index oxidized material constituting the lens. A high reflecting coating 86 and anti-reflecting coating 87 may then be deposited on the end faces of the device as required.

CLAIMS

1. A lens comprising a region of semiconductor material shaped by selective oxidation of a layer of semiconductor material so as to leave said region of semiconductor material unoxidized and adapted to focus a beam of radiation.

2. A lens according to claim 1, wherein the shaped region of unoxidized semiconductor material and one or more adjacent regions of oxidized semiconductor material define a refractive index interface which serves to focus the beam of radiation.

3. A lens according to claim 1, wherein the shaped region of unoxidized semiconductor material defines a refractive index interface with air, as a result of removal of oxidized semiconductor material, which serves to focus the beam of radiation.

4. A lens according to claim 1, 2 or 3, wherein the layer of semiconductor material has a composition which is graded across the layer such that the oxidation rate of the material varies across the layer.

5. A lens according to claim 4, wherein the layer of semiconductor material is constituted by an aluminium alloy with an aluminium content which varies across the layer.

6. A lens according to claim 5, wherein the aluminium alloy is AlGaAs.

7. A lens according to claim 4, 5 or 6, wherein the layer of semiconductor material comprises a series of sublayers of semiconductor material differing in the proportion of a common constituent of each sublayer such that said proportion varies monotonically across the layer from a minimum value to a maximum value.

8. A lens according to claim 7, wherein said sublayers of semiconductor material are separated by intermediate sublayers of semiconductor material which does not contain said constituent.

9. A lens according to any one of claims 1 to 8, which is integrally formed with a surface emitting optoelectronic device.

10. A lens according to any one of claims 1 to 8, which is integrally formed with an edge emitting optoelectronic device.

11. A method of forming a lens comprising growing a layer of semiconductor material, and selectively oxidizing the semiconductor material of the layer so as to form a region of unoxidized semiconductor material which is shaped to focus a beam of radiation.

12. A method according to claim 11, wherein the oxidized and unoxidized regions of the layer define a refractive index interface in the finished lens which serves to focus the beam of radiation.

13. A method according to claim 12, which includes the further step of removing the oxidized semiconductor material so that the shaped region of unoxidized semiconductor material defines a refractive index interface with the surrounding air in the finished lens which serves to focus the beam of radiation.

14. A method according to claim 11, 12 or 13, wherein the layer of semiconductor material is grown such that its composition is graded across the layer so that, during the subsequent oxidizing step, parts of the layer are oxidized at a greater rate than other parts of the layer.

15. A method according to claim 14, wherein the layer of semiconductor material is constituted by an aluminium alloy with an aluminium content which varies across the layer.

16. A method according to claim 14 or 15, wherein the layer of semiconductor material is grown in the form of a series of sublayers of semiconductor material differing in the proportion of a common constituent of each sublayer such that said proportion varies monotonically across the layer from a minimum value to a maximum value.

17. A method according to claim 16, wherein the layer of semiconductor material is grown in the form of said sublayers separated by intermediate sublayers of semiconductor material which does not contain said constituent.

18. A method according to any one of claims 11 to 17, wherein the layer of semiconductor material is grown on a surface of a surface emitting optoelectronic device so that the lens is integrally formed with said device.

19. A method according to any one of claims 11 to 17, wherein the layer of semiconductor material is grown on an edge facet of an edge emitting optoelectronic device so that the lens is integrally formed with said device.

20. An optical system comprising a surface emitting optoelectronic device, and a lens according to any one of claims 1 to 8 which is integrally formed with said surface emitting optoelectronic device.

21. An optical system comprising an edge emitting optoelectronic device, and a lens according to any one of claims 1 to 8 which is integrally formed with said edge emitting optoelectronic device.

22. A method of forming an optical system comprising the steps of forming a surface emitting optoelectronic device, and forming a lens by a method according to any one of

claims 11 to 17, wherein the layer of semiconductor material is grown on a surface of said surface emitting optoelectronic device so that said lens is integrally formed with said surface emitting optoelectronic device.

23. A method of forming an optical system comprising the steps of forming an edge emitting optoelectronic device, and forming a lens by a method according to any one of claims 11 to 17, wherein the layer of semiconductor material is grown on an edge facet of said edge emitting optoelectronic device so that said lens is integrally formed with said edge emitting optoelectronic device.

The Patent Office

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Application No: GB 9715117.9
Claims searched: All

Examiner: C.D.Stone
Date of search: 10 September 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): H1K(KQAME,KQAMX);G2J(JB7CX)

Int Cl (Ed.6): H01L

Other: ON LINE,W.P.I.

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	US 4025157 U.S.A. Sec. of Navy	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.